

Thermal Data Interoperability for Small Satellite Missions: Integrating CAD, ETMS, and STEP-TAS

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Abstract—The development cycles of small satellite missions demand a transition from siloed engineering practices toward concurrent, model-based systems engineering (MBSE). Thermal engineering remains a persistent bottleneck: mechanical-to-thermal model translation is largely manual, and the exchange of thermal models between solver environments is brittle, leading to data loss, longer schedules, and integration errors. This paper presents an implemented methodology for streamlining the thermal analysis workflow through three data-exchange capabilities deployed in commercial use: import of CAD geometry from STEP files; import of ESATAN-TMS thermal models in the ETMS format; and import of thermal models in the ESA-supported STEP-TAS neutral exchange format. We describe the geometric simplification, material/optical-property reconciliation, and unit-normalisation steps that make these pipelines robust in practice, and report qualitative outcomes from two recent commercial small-satellite engagements (customer names withheld). The result is a reduction in modelling lead time and improved consistency across multi-partner consortia, supporting compliance with European agency standards.

Keywords—small satellite, thermal analysis, MBSE, model interoperability, STEP, STEP-TAS, ESATAN-TMS, ETMS, ECSS, neutral format

I. INTRODUCTION

The small satellite sector has undergone a structural shift over the past decade. Constellations of dozens to hundreds of platforms are now routinely manufactured under aggressive schedule and cost constraints, with mission concept-to-launch timelines compressed from years to months. This pace is incompatible with the document-centric, sequentially staged engineering workflow inherited from larger institutional missions [1], [2].

Thermal control engineering is one of the disciplines most exposed to this tension. A thermal mathematical model (TMM) typically lags the mechanical CAD baseline by weeks because geometry is reconstructed manually inside the thermal solver. When the same model must be exchanged with a partner organisation that uses a different solver, or delivered to an agency that requires a neutral representation, the data path is again manual and lossy. ECSS standards on thermal control [3] and on space engineering data interchange [4] increasingly mandate traceable, machine-readable exchange — yet tool support

for the relevant formats remains uneven across the commercial ecosystem.

This paper reports on three data-exchange capabilities implemented in Radian’s thermal analysis software, addressing the three highest-friction transitions in a typical small-satellite thermal workflow:

- mechanical-to-thermal: import of solid geometry from STEP files, with automatic simplification into thermal primitives;
- cross-solver: import of ESATAN-TMS datasets in the ETMS format, so that models authored in ESATAN-TMS can be continued and extended in a complementary environment;
- agency-compliant ingestion: parsing of STEP-TAS files, the ESA-supported neutral thermal exchange format, so that models received from prime contractors and agency partners can be opened directly without bespoke conversion.

Section II reviews the relevant standards and prior practice. Section III describes the three pipelines, including geometric simplification, material and surface property reconciliation, and unit normalisation. Section IV summarises two commercial engagements in which these capabilities have been used end-to-end. Sections V and VI close with a discussion of fidelity, lessons learned, and future work.

II. BACKGROUND AND RELATED STANDARDS

A. Mechanical-to-Thermal Translation

Mechanical CAD is the authoritative source for spacecraft geometry, typically managed in commercial PLM systems and exchanged across the supply chain through ISO 10303 (STEP) AP203 or AP242 part files [5]. Thermal solvers, however, do not consume mechanical CAD directly. A thermal model is a topologically reduced representation: large numbers of B-rep faces collapse into a small set of nodes connected by linear and radiative couplings. Constructing this representation manually is the principal driver of thermal-team workload during preliminary design and represents the dominant source of model-vs-CAD drift through the programme.

B. ESATAN-TMS and the ETMS Format

ESATAN-TMS is a widely used European solver for spacecraft thermal analysis [6], and the ETMS file format is broadly established across European primes and ESA-funded programmes. Many small-satellite teams

operate ESATAN-TMS internally, receive ETMS deliveries from suppliers, or carry forward ETMS datasets from earlier mission phases. The ability to ingest these datasets without retyping is a hard requirement for cross-tool collaboration in the commercial segment.

C. STEP-TAS as a Neutral Exchange Format

STEP-TAS (ISO 10303-433) is the ESA-supported neutral format for thermal analysis data [7], [8]. Its scope covers geometric primitives, optical and thermo-physical properties, mass budgets, and the structural relationships between them. STEP-TAS is the format requested by ESA in MBSE-driven procurements and is increasingly cited in subcontract data requirement lists for European consortia. Adopting STEP-TAS as a first-class import target — rather than negotiating bilateral conversions per partnership — is therefore a structural simplification of the consortium-level data flow on the receiving side. Closing the loop with a STEP-TAS exporter is the planned next step (Section V).

III. DATA EXCHANGE CAPABILITIES

The three pipelines share a common architectural pattern. A neutral in-memory thermal model — comprising parts, geometries, nodes, faces, materials, and surface properties — sits at the centre. Each of the three importers translates an external representation into this neutral form. A STEP-TAS exporter performing the reverse mapping for outbound delivery is on the short-term roadmap (Section V).

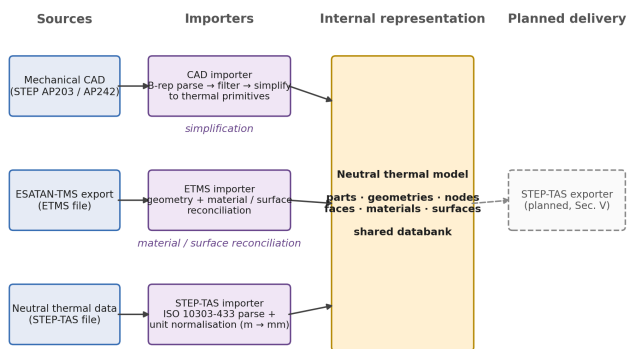


Fig. 1. Workflow diagram of the three pipelines

A. CAD Geometry Import from STEP Files

STEP files routinely contain hundreds to thousands of faces per assembly, including fasteners, internal pockets, and manufacturing features that are immaterial to a thermal model. The importer therefore proceeds in three stages: an initial parse that builds a B-rep representation of the assembly; a filtering stage that discards bodies below a configurable volume threshold and removes degenerate shells and internal faces; and a simplification stage that attempts to deduce a parametric primitive (box, plate, cylinder, disc, sphere, triangle) for each remaining body.

Each surviving primitive is registered as a geometry inside a part, with a single thermal node placed at its centroid by default. Faces are instantiated per geometry side and left available for surface-property assignment by the user. The simplification step is configurable per geometry: a user can override the auto-deduced primitive, replace it with a different shape, or discard it by name or by volume. Bounding-box and colour metadata are preserved through the simplification chain so the thermal engineer can

correlate the reduced model back to the originating CAD body without re-opening the source file.

The pipeline is executed asynchronously: large assemblies routinely take minutes to parse and simplify, and progress is reported to the user incrementally. No automatic mesh generation is performed; multi-node discretisation is left as an explicit user action so that the analyst controls model granularity rather than inheriting it from the mechanical tessellation.

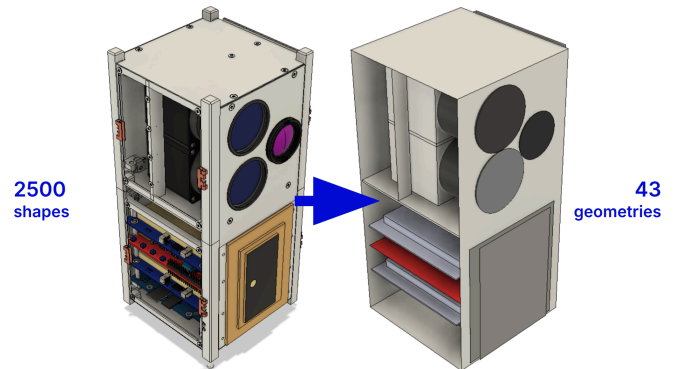


Fig. 2. STEP assembly (left) vs. simplified thermal model (right, auto-deduced primitives)

B. ESATAN-TMS Model Import

The ETMS importer parses an ESATAN-TMS export in the ETMS format and translates each ETMS geometry record into the neutral thermal model. Type strings characteristic of ETMS — for example shell-cylinder, shell-cone, solid-box — are mapped to the corresponding internal primitive type, and morphology (solid versus shell) is carried through so that face counts match the ETMS source. Dimensions are converted from metres to the internal millimetre representation, and ESATAN-TMS colour identifiers are mapped to a hexadecimal palette so that the visual identity of the model is preserved.

The non-trivial part of the import is the reconciliation of materials and optical surfaces. ETMS files reference materials and surfaces by name, but the same physical aluminium alloy or black paint may appear under different names across datasets received from different sources. The importer first collects the set of unique material and surface references from the ETMS file. Each reference is then matched against the company’s thermal Databank, first by identifier and, on failure, by physical property tuple — density, specific heat, and conductivity for materials; emissivity and absorptance for surfaces. Only when no match exists is a new Databank entry created, which prevents the silent proliferation of duplicate materials over time.

Geometries with array suffixes (for example a part repeated as instances “bracket, 1”, “bracket, 2”, ...) are grouped under a single part so that the imported model preserves the assembly hierarchy of the source. Geometric topology, material assignment, and surface optical properties round-trip cleanly; ETMS-specific solver constructs such as boundary conditions and explicit conductors are not currently carried across, and are flagged to the user at import time.

C. STEP-TAS Import

The STEP-TAS importer parses an ISO 10303-433 representation into the neutral thermal model. Geometry type, morphology, position, orientation, dimensions, and

per-side face information are read directly. Nodes are reconstructed from their bounding ranges in local coordinates so that multi-node geometries — those carrying a mesh grid — preserve the spatial granularity of the source file. Material thermo-physical properties (density, specific heat, conductivity) and optical surface properties (emissivity, absorptance, specular reflectivity for diffuse-grey surfaces) are ingested alongside the geometry references that consume them and reconciled against the shared Databank using the same property-tuple matching applied on the ETMS path.

Coordinates are converted from the SI metres convention required by STEP-TAS to the internal millimetre representation. Mass budgets carried by the source file are validated against the geometric primitives and densities; discrepancies are flagged to the user rather than silently overwritten, allowing reviewers to detect mass-versus-capacitance inconsistencies introduced upstream. Header metadata — preprocessor identifier, originating system, authors, organisations, and timestamp — is preserved as provenance on the imported model.

The current scope of the importer is geometry plus radiative surface properties. Linear conductors and explicit thermal links — when present in the source file — are not yet ingested; closing this gap is part of the planned roadmap (Section V) and will be addressed jointly with the addition of the corresponding exporter. Within its current scope, the importer has been validated against STEP-TAS reference files produced by ESA-side tooling and reproduces the source geometry without further conversion.

IV. DISCUSSION AND LESSONS LEARNED

A. Fidelity and Round-Trip Behaviour

Across the two engagements, geometric topology and material/optical properties were preserved cleanly when ingesting from CAD STEP, ETMS, and STEP-TAS sources. The principal residual friction in current scope is the absence of explicit thermal-link representation: where a partner organisation exchanges a fully closed thermal mathematical model, the conductor network must currently be reconstructed downstream of the import. This was tolerable in both engagements because the receiving teams ran their own conductor-generation step, but it is the single most-requested addition to the import scope and will be addressed jointly with the planned exporter.

B. Material and Surface Reconciliation

The most consequential implementation decision was to deduplicate materials and surfaces against a shared Databank rather than to import them verbatim. Without this step, a year of imports produces a Databank in which the same physical aluminium alloy is represented half a dozen times under near-identical names, each carrying microscopic property differences inherited from different sources. The reconciliation discipline cost a small amount of import-time complexity in exchange for sustained model hygiene.

C. Geometric Simplification as a User Decision

Auto-simplification is necessary but not sufficient. Even with aggressive volume thresholds, mechanical CAD contains structures — connectors, hinges, harness routings

— for which there is no objectively correct thermal primitive. Treating the auto-deduced shape as a recommendation rather than a commitment, and exposing override actions to the analyst, was indispensable. The same observation applied to multi-node discretisation, which was left explicit rather than inferred from CAD tessellation.

V. CONCLUSION AND FUTURE WORK

A practical thermal-data interoperability framework has been described, covering CAD geometry import from STEP, ESATAN-TMS model import via the ETMS format, and STEP-TAS import. The three capabilities have been deployed in commercial small-satellite engagements, where they have removed geometry construction from the critical path of the thermal analysis cycle and made models received from ESA-aligned partners directly usable without bilateral conversion arrangements.

Three extensions are planned. First, a STEP-TAS exporter will be added in the short term, completing round-trip exchange and enabling deliveries to agency partners in their preferred neutral format; initial coverage will mirror that of the importer (geometry plus radiative surface properties), with subsequent iterations extending to non-geometrical nodes and conductive and radiative couplings. Second, the ETMS import path will be complemented by an ETMS export path, allowing the environment to be inserted alongside ESATAN-TMS as a complementary analysis layer rather than a one-way endpoint. Third, conductor and thermal-link representation will be unified across all importers and exporters so that fully closed thermal mathematical models flow through the neutral hub without loss.

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REFERENCES

- [1] A. Poghosyan and A. Golkar, "CubeSat evolution: Analyzing CubeSat capabilities for conducting science missions," *Progress in Aerospace Sciences*, vol. 88, pp. 59–83, 2017.
- [2] INCOSE, *Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities*, 5th ed. Hoboken, NJ: Wiley, 2023.
- [3] European Cooperation for Space Standardization, "Thermal control general requirements," ECSS-E-ST-31C, ESA-ESTEC, Noordwijk, The Netherlands, 2008.
- [4] European Cooperation for Space Standardization, "Space engineering — Thermal analysis handbook," ECSS-E-HB-31-03A, ESA-ESTEC, Noordwijk, The Netherlands, 2016.
- [5] ISO 10303-242:2022, "Industrial automation systems and integration — Product data representation and exchange — Part 242: Application protocol: Managed model-based 3D engineering," International Organization for Standardization, Geneva, 2022.
- [6] ITP Engines UK, *ESATAN-TMS Thermal Engineering Manual*, Whetstone, U.K., 2023.
- [7] ISO 10303-433:2014, "Industrial automation systems and integration — Product data representation and exchange — Part 433: Application module: AP203 thermal analysis (STEP-TAS)," International Organization for Standardization, Geneva, 2014.
- [8] H.-P. de Koning, "STEP-TAS: a neutral file format for thermal analysis data," in *Proc. 18th European Workshop on Thermal and ECLS Software*, ESA-ESTEC, Noordwijk, 2004.
- [9] European Cooperation for Space Standardization, "Space engineering — System engineering general requirements," ECSS-E-ST-10C Rev. 1, ESA-ESTEC, Noordwijk, The Netherlands, 2017.
- [10] NASA, *NASA Systems Engineering Handbook*, NASA/SP-2016-6105 Rev. 2, Washington, DC, 2016.